AFRL-SN-WP-TR-1999-1067

ROLL-TO-ROLL, PROJECTION LITHOGRAPHY SYSTEM FOR HIGH-RESOLUTION PATTERNING OF FLEXIBLE SUBSTRATES, VOLUME 1

K. JAIN, T. J. DUNN, N. FARMIGA AND M. ZEMEL

ANVIK CORPORATION
6 SKYLINE DRIVE
HAWTHORNE, NY 10532

MAY 1999

FINAL REPORT FOR JANUARY 1996 - MAY 1999

Approved for public release; distribution unlimited

SENSORS DIRECTORATE
AIR FORCE RESEARCH LABORATORY
AIR FORCE MATERIEL COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OH 45433-7322

NOTICE

USING GOVERNMENT DRAWINGS, SPECIFICATIONS, OR OTHER DATA INCLUDED IN THIS DOCUMENT FOR ANY PURPOSE OTHER THAN GOVERNMENT PROCUREMENT DOES NOT IN ANY WAY OBLIGATE THE US GOVERNMENT. THE FACT THAT THE GOVERNMENT FORMULATED OR SUPPLIED THE DRAWINGS, SPECIFICATIONS, OR OTHER DATA DOES NOT LICENSE THE HOLDER OR ANY OTHER PERSON OR CORPORATION; OR CONVEY ANY RIGHTS OR PERMISSION TO MANUFACTURE, USE, OR SELL ANY PATENTED INVENTION THAT MAY RELATE TO THEM.

THIS REPORT IS RELEASABLE TO THE NATIONAL TECHNICAL INFORMATION SERVICE (NTIS). AT NTIS, IT WILL BE AVAILABLE TO THE GENERAL PUBLIC, INCLUDING FOREIGN NATIONS.

THIS TECHNICAL REPORT HAS BEEN REVIEWED AND IS APPROVED FOR PUBLICATION.

JOSEPH E. BRANDELIK, Project Engineer
Multi-Chip Integration Branch
Aerospace Components Division

ALAN J. TEWKSBURY, Chief
Multi-Chip Integration Branch
Aerospace Components Division

ROBERT T. KEMERLEY, Chief
Aerospace Components Division
Sensors Directorate

Do not return copies of this report unless contractual obligations or notice on a specific document require its return.

REPORT DOCUMENTATION PAGE			*Form Approved OMB No. 0704-0188*
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.			
1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE MAY 1999	3. REPORT TYPE AND DATES COVERED FINAL REPORT, JANUARY 1996 - MAY 1999	
4. TITLE AND SUBTITLE ROLL-TO-ROLL, PROJECTION LITHOGRAPHY SYSTEM FOR HIGH-RESOLUTION PATTERNING OF FLEXIBLE SUBSTRATES, VOLUME 1			5. FUNDING NUMBERS C: F33615-96-C-1802 PE: 63739 PR: ARPE TA: 04 WU: 01
6. AUTHOR(S) K. JAIN, T. J. DUNN, N. FARMIGA AND M. ZEMEL			
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) ANVIK CORPORATION 6 SKYLINE DRIVE HAWTHORN, NY 10532			8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) SENSORS DIRECTORATE AIR FORCE RESEARCH LABORATORY AIR FORCE MATERIEL COMMAND WRIGHT-PATTERSON AFB, OH 45433-7322 POC: JOSEPH BRANDELIK, AFRL/SNDI, 937-255-4557			10. SPONSORING/MONITORING AGENCY REPORT NUMBER AFRL-SN-WP-TR-1999-1067
11. SUPPLEMENTARY NOTES THIS EFFORT WAS FUNDED BY THE DEFENSE ADVANCED RESEARCH PROJECTS AGENCY (DARPA) VOLUME 2 IS LIMITED TO U.S. GOVERNMENT AGENCIES ONLY			
12a. DISTRIBUTION AVAILABILITY STATEMENT CLEARED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED			12b. DISTRIBUTION CODE
13. ABSTRACT *(Maximum 200 words)* This Final Report describes the ANVIK 3100 SRE roll-to-roll lithography system which was shipped to Sheldahl, Inc. (Longmont, CO) in May 1998. The machine is currently being phased into Sheldahl's production facilities where it willl be used for microelectronic fabricationon flexible substrates. In the Report, a general overview of the system is presented			
14. SUBJECT TERMS EXCIMER LASER, LITHOGRAPHY, FLEXIBLE SUBSTRATES, PATTERNING			15. NUMBER OF PAGES 22 16. PRICE CODE
17. SECURITY CLASSIFICATION OF REPORT UNCLASSIFIED	18. SECURITY CLASSIFICATION OF THIS PAGE UNCLASSIFIED	19. SECURITY CLASSIFICATION OF ABSTRACT UNCLASSIFIED	20. LIMITATION OF ABSTRACT SAR

TABLE OF CONTENTS

ACKNOWLEDGMENTS

Anvik Corporation gratefully acknowledges support from the Defense Advanced Research Projects Agency and numerous helpful interactions with Sheldahl, Inc. We would also like to thank James Murphy from the Defense Advanced Research Projects Agency (DARPA), James Grote from Air Force Research Laboratory's Materials and Manufacturing Directorate at Wright Patterson Air Force Base, and Joseph Brandelik from the Air Force Research Laboratory's Sensors Directorate at Wright Patterson Air Force Base for their assistance in this program.

1. Introduction

Flexible circuits are finding rapidly growing use in communication devices, automotive electronics, and a variety of military systems enabling products that are lighter, more durable, and conformable while significantly reducing costs. Patterning on continuous rolls of flexible materials offers substantial challenges, but if accomplished efficiently, can provide many additional cost benefits: first, roll-to-roll processing (also widely called web processing) minimizes contamination due to reduced handling, and consequently, improves yields; second, web processing is inherently more suited for high-speed automated processes, which reduces direct labor and increases throughput; and third, the non-exposure overhead time is minimized since the load and unload operations are simultaneous and simpler. All of these advantages lead to substantial reductions in manufacturing costs.

In the manufacturing of electronic products in large-format processing, on flexible as well as rigid substrates, it is necessary to fabricate millions of microscopic structures on a large panel. Ideally, one desires a large-area lithography system that can provide the required resolution over the entire substrate with high processing throughput. The patterning technology used determines not only the ultimate performance of the product (e.g., pixel density in a display or interconnect density in a printed circuit or multichip module), but also the economics of the entire manufacturing process through such key factors as yield and throughput. These performance and economic considerations at the module level ultimately influence the size and cost at the system level.

Other than the Anvik system described here, no lithography system currently exists that meets all the desired performance criteria satisfactorily, especially for patterning on flexible materials. Exposure tools currently used in the fabrication of electronic devices on flexible substrates, including contact printers, steppers, and direct-write tools, suffer from significant limitations, including one or more of the following: defect generation on the substrate, mask life degradation, long vacuum pull-down times, limited substrate size capability, limited resolution, low throughput, stitching errors, poor yield, high system cost, poor optomechanical performance, and inability to drill vias in batch mode.

We have developed a novel lithography system that is capable of high-throughput projection imaging on continuous, flexible substrates in a roll-to-roll configuration. The system provides both large-area, high-resolution patterning in photoresists and via formation by photo-ablation in dielectrics, eliminating limitations of existing lithography tools. The modular design of the new system also provides equipment upgradability as well as choice of user-specified system configurations suitable for different roll widths and minimum feature sizes. These results are achieved with the combination of three key novel system features: a hexagonal seamless scanning projection imaging technology, a single-planar stage system configuration, and a roll-to-roll substrate handling system. These features provide high optical and scanning efficiencies as well as low overhead times, enabling processing throughputs as high as 4 sq. ft./min. The new lithography system is highly attractive for cost-effective production of a wide variety of microelectronic products on flexible substrates, including printed circuits, multichip modules, and displays.

2. System Overview

In this section we describe the new lithography system technology that provides both large-area projection imaging capability with the desired resolution and the ability to handle flexible substrates in a roll-to-roll configuration. We first describe our broad large-area lithography technology applicable to discrete panels, and then show how that is modified and extended to incorporate flexible, roll-fed materials.

Figure 1 illustrates Anvik's new patterning system technology. The substrate and mask are mounted on a single planar stage which is capable of moving in both x- and y-directions. The illumination system has an emission plane in the shape of a hexagon. A 1:1 projection lens images the illuminated hexagonal pattern on the mask on to the substrate. The single planar stage causes the mask and the substrate to scan in unison along the x-axis across their respective illumination regions to traverse the substrate length. The stage then moves along y by an effective scan width (shown as w in Fig. 2). Now the substrate and mask are again scanned along x as before, after which they are laterally moved along y, and the process is repeated until the entire substrate is exposed. The complementary overlap between adjacent hexagonal scans produces a totally seamless and uniform exposure over the whole substrate.

Figure 2 illustrates the seamless scanning mechanism in more detail. The hexagons and represent the illuminated regions on the substrate for scan 1 and scan 2. The y-movement after each x-scan is given by $w = 1.5\ l_h$, where l_h is the hexagon side-length. In scan 1, the region swept by the rectangular portion b-g-h-c of hexagon 36 is not overlapped by any portion of scan 2. However, the region swept by the triangular segment a-b-c of hexagon 36 in scan 1 is re-swept in scan 2 by the triangular segment d-e-f of hexagon 38. When the doses from these triangular segments are integrated, the cumulative exposure dose anywhere in the overlapping region is the same as in the non-overlapping regions, thus producing a seamless, uniform exposure over the whole substrate.

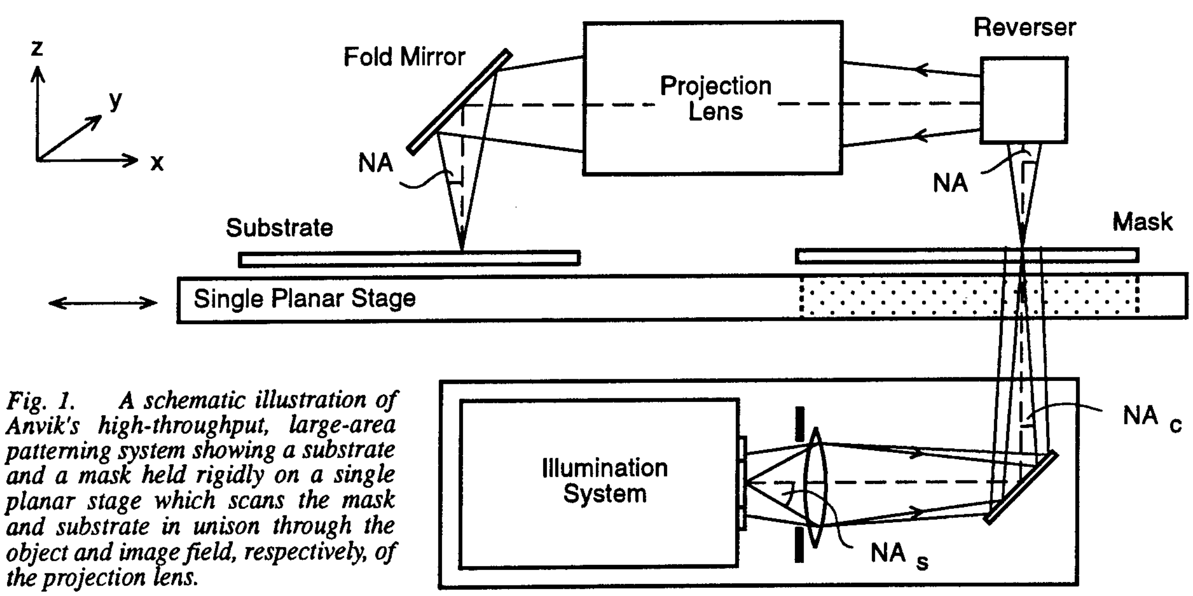


Fig. 1. A schematic illustration of Anvik's high-throughput, large-area patterning system showing a substrate and a mask held rigidly on a single planar stage which scans the mask and substrate in unison through the object and image field, respectively, of the projection lens.

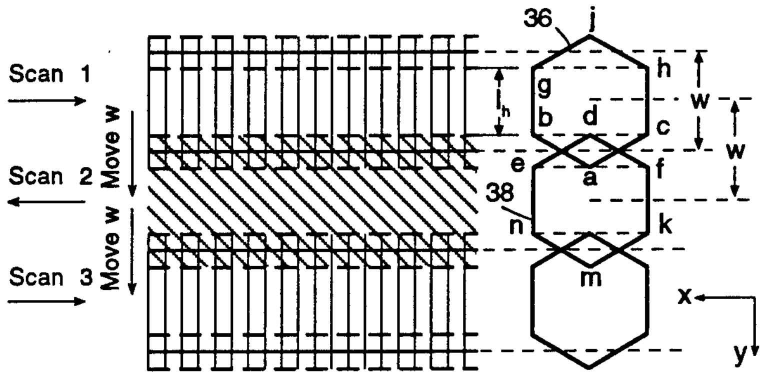


Fig. 2. Anvik's seamless scan-and-repeat mechanism, showing three successive scans and complementary exposure in the overlap area between adjacent hexagonal imaging regions.

The Anvik lithography technology employing hexagonal seamless scanning and single planar stage configuration enables the user to achieve the desired resolution over very large substrate areas efficiently. We next describe how we have accomplished the integration of this technology with roll-to-roll material handling for high-throughput patterning on flexible substrates.

Figure 3 presents a schematic view of the web-handling for the new large-area projection lithography system. The flexible substrate is fed from the supply roller, extends across the exposure region on the scanning stage, and is wound onto the take-up roller. During exposure, the segment (panel) of the flexible substrate being exposed is held rigidly on the scanning stage by vacuum. As described previously in this section, the illumination system produces a hexagonal illumination region on the mask which is imaged by the projection lens on to the substrate. When this is combined with the serpentine scan of the stage, the entire mask pattern is transferred to the substrate. After the exposure of a panel segment is complete, the vacuum is released and the flexible substrate is advanced to expose the next segment of the roll material.

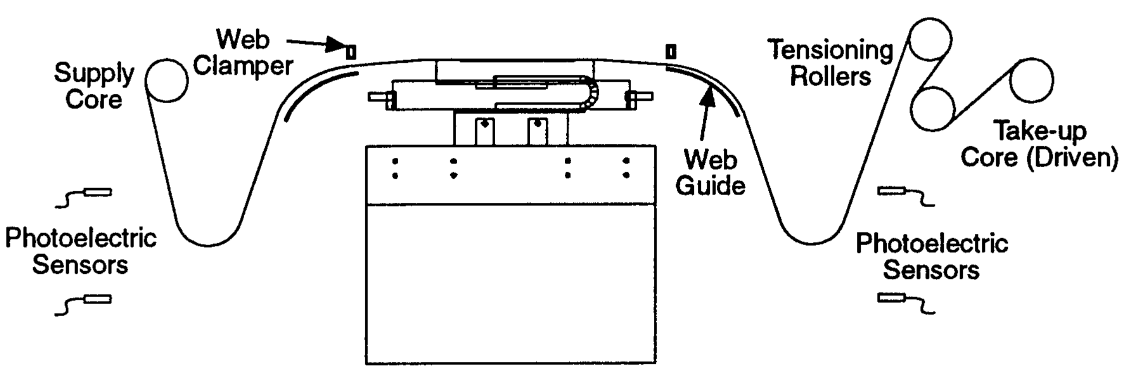


Fig. 3. The flexible substrate is fed from the supply core, goes through a slack loop and across the scanning platform where it is vacuum-clamped during exposure. On the other side, the web goes through another slack loop before being wound onto the take-up roller.

It is necessary to take into account the fact that the substrate is a continuous roll, rather than a discrete panel. The objective is to hold a panel-segment of the web material rigidly locked on the stage during the exposure process, and still permit unhindered movement of the stage along both x- and y-directions. This is accomplished with the web-handling configuration illustrated in Fig. 3.

After a new panel-segment of the flexible material is locked into place on the stage, the take-up and supply rollers unwind by a predetermined amount to introduce a certain amount of slack to the roll material on either side of the exposure segment. As the stage scans along the x-direction, the slack on one side of the stage decreases and is added to the slack on the other side of stage. This allows the stage to move unimpeded by the portions of the flexible substrate which are not locked to the stage, and prevents any stress to the material which is locked to the stage. Once a scan is complete, the stage steps along the y-direction for the next scan along the x-axis. The slack on either side of the stage is designed to be large enough to allow the y-motion to occur unhindered and without harming the flexible material. The y-movement of the stage will temporarily introduce some twist to the flexible substrate in the slack regions; therefore, the slack lengths are carefully designed to avoid wrinkling or kinking of the roll material. Note that the supply and take-up rollers remain stationary, and, like the projection lens and the illumination system, remain fixed in space. The only moving components are the scanning stage and the flexible substrate on either side of the stage.

Thus, the new lithography system described here for patterning flexible materials not only delivers the advantages of projection imaging with high resolution over large areas, but also enables handling of the flexible material in a roll-to-roll configuration, thereby minimizing yield losses caused by contamination and greatly increasing throughput by reducing material handling overhead time.

3. System Description

In this section we present a detailed description of the roll-to-roll lithography system we have designed and built for patterning on flexible materials for production of communication microelectronics. The overall specifications of the system are presented in Table 1. The projection lens has a numerical aperture of 0.025 which provides a resolution capability of 10 μm. The web-handling unit in this lithography system is designed for flexible materials with a roll-width of 340 mm (13.4 inches), but the design can easily be modified to process wider or narrower substrate rolls. The size of a panel of the flexible material processed in each exposure sequence is designed to be 315 x 315 mm (12.5 x 12.5 inches); this size can easily be increased or decreased as required. The light source is a high-power XeF excimer laser with a wavelength of 351-353 nm. The system is designed with an automatic alignment system that provides better than 2.5 μm overlay. Based on demonstrated parameters, the lithography system is projected to be able to provide a throughput of 4.0 sq. ft/min. Below we describe the detailed design parameters, both optical and mechanical, for this system and discuss its key hardware subsystems.

The light source is a commercially available, high-power, XeF excimer laser; for this lithography system we have selected a Lambda Physik Series 4000 laser with a wavelength of 351 - 353 nm. It operates at a repetition rate of 300 Hz with a pulse energy of 250 mJ/pulse and an average output power of 75 W. A beam delivery system consisting of several spherical and cylindrical lenses transmits the output of the light source to a beam-uniformizer that transforms the nonuniform input beam into a hexagonal shape and homogenizes it across its transverse spatial profile. A condenser lens system then magnifies and images the output of the homogenizer onto the mask mounted on the planar stage. The projection lens images the portion of the mask illuminated by the homogenized beam onto the substrate which is also rigidly held on the same planar stage.

Table 1. Specifications of Anvik 3100 SRE

Imaging Concept	Hexagonal seamless scanning projection
Resolution	10 μm (0.4 mil)
Projection System	1:1 magnification refractive lens
Numerical Aperture	0.025 (f/20)
Depth of Focus	560 μm (22.4 mils)
Lens Image Field Size	50 mm (2 inches) diameter
Width of Substrate Roll	340 mm (13.4 inches)
Panel Exposure Area	315 X 315 mm (12.5 X 12.5 inches)
Illumination Source	XeF excimer laser
Illumination Wavelength	351 - 353 nm
Overlay Precision	± 2.5 μm (0.1 mil)
Alignment System	Automatic
Panel and Mask Handling	Automatic
Throughput	4 sq. ft/min (220 panels/hr)

The projection lens is an eight-element, all-refractive optical system with unit magnification. It is designed to be telecentric in both image and object space so that the magnification is insensitive to focus adjustments. The design of the lens has been achromatized for the full spectral bandwidth of the laser by use of different optical materials to fabricate the elements; this provides maximum utilization of the available laser power. The lens has been designed with an NA of 0.025, providing diffraction-limited resolution of 10 μm and a depth of focus greater than 0.5 mm. All elements in the lens assembly are coated with multilayer dielectric anti-reflection coatings to maximize the optical transmission of the lens at the design wavelength.

The single planar stage system is an air-bearing x-y stage configured as an x-stage (scanning) stacked on a y-stage (stepping). The travel ranges of the x- and y-stages are 500 mm and 350 mm, respectively. With these travel ranges it is possible to expose panels of sizes up to 380 x 355 mm (15 X 14 inches). Larger panel sizes can be accommodated by integrating stages with appropriately larger ranges of travel. The stage can scan with velocities up to 400 mm/sec. The stage utilizes a glass-scale encoder providing feedback to a PC control card which is plugged into the control computer. The stage holds the scanning platform which locates the mask and the substrate side-by-side, horizontally, in the same plane. A key advantage of this design is that it does not require stages with very high precision in positioning or scan velocities and the system is relatively insensitive to reasonable amounts of pitch and roll errors. This makes it possible to use commercially available air-bearing systems at reasonable costs.

A brief description of the web-handling system has already been given above in Sec. 2. The ability to process continuous rolls of flexible materials is a unique feature of this lithography system, and is made possible by the open architecture and modularity of the overall system design. This modularity also enables us to readily design and incorporate a material handling system for substrates of any desired roll-widths, both smaller and larger than the specification of 340 mm for the system described here.

Other components in the full optomechanical system include a bridge that straddles over the mask-substrate platform and supports the projection lens, reverser system, fold mirror, and alignment system. All reflective surfaces in the complete optical train are coated with high-reflectivity multilayer dielectric coatings and all transmissive surfaces with anti-reflection multilayer dielectric coatings. The alignment system employs a vision system that locates a set of fiducial targets on the mask and substrate, and then initiates instructions to produce the necessary x-y-θ movement of the substrate panel relative to the mask to bring the two in alignment.

4. CONCLUSIONS

We have developed a novel lithography system that is capable of high-throughput projection imaging on continuous, flexible substrates in a roll-to-roll configuration. The system provides both large-area, high-resolution patterning in photoresists and via formation by photo-ablation in dielectrics, eliminating limitations of lithography tools currently used in the production of flexible circuits. The unique, modular design of the new system also provides equipment upgradability as well as choice of user-specified system configurations. These results are achieved with the combination of three key novel system features: a hexagonal seamless scanning projection imaging technology, a single-planar stage system configuration, and a roll-to-roll substrate handling system. These features provide high optical and scanning efficiencies as well as low overhead times, enabling processing throughputs as high as 4 sq. ft./min. This lithography system is highly attractive for cost-effective production of a wide variety of microelectronic products on flexible substrates, including printed circuits, multichip modules, and displays.

5. Appendix: U.S. Patent No. 5,652,645

US005652645A

United States Patent [19]

Jain

[11] **Patent Number: 5,652,645**

[45] **Date of Patent: Jul. 29, 1997**

[54] **HIGH-THROUGHPUT, HIGH-RESOLUTION, PROJECTION PATTERNING SYSTEM FOR LARGE, FLEXIBLE, ROLL-FED, ELECTRONIC-MODULE SUBSTRATES**

[75] Inventor: **Kanti Jain**, Elmsford, N.Y.

[73] Assignee: **Anvik Corporation**, Hawthorne, N.Y.

[21] Appl. No.: **506,232**

[22] Filed: **Jul. 24, 1995**

[51] **Int. Cl.**^{6} **G03B 27/42**; G03B 27/44; G03B 27/48

[52] **U.S. Cl.** **355/53**; 355/54; 355/50; 355/72

[58] **Field of Search** 355/53, 54, 64, 355/72, 73

[56] **References Cited**

U.S. PATENT DOCUMENTS

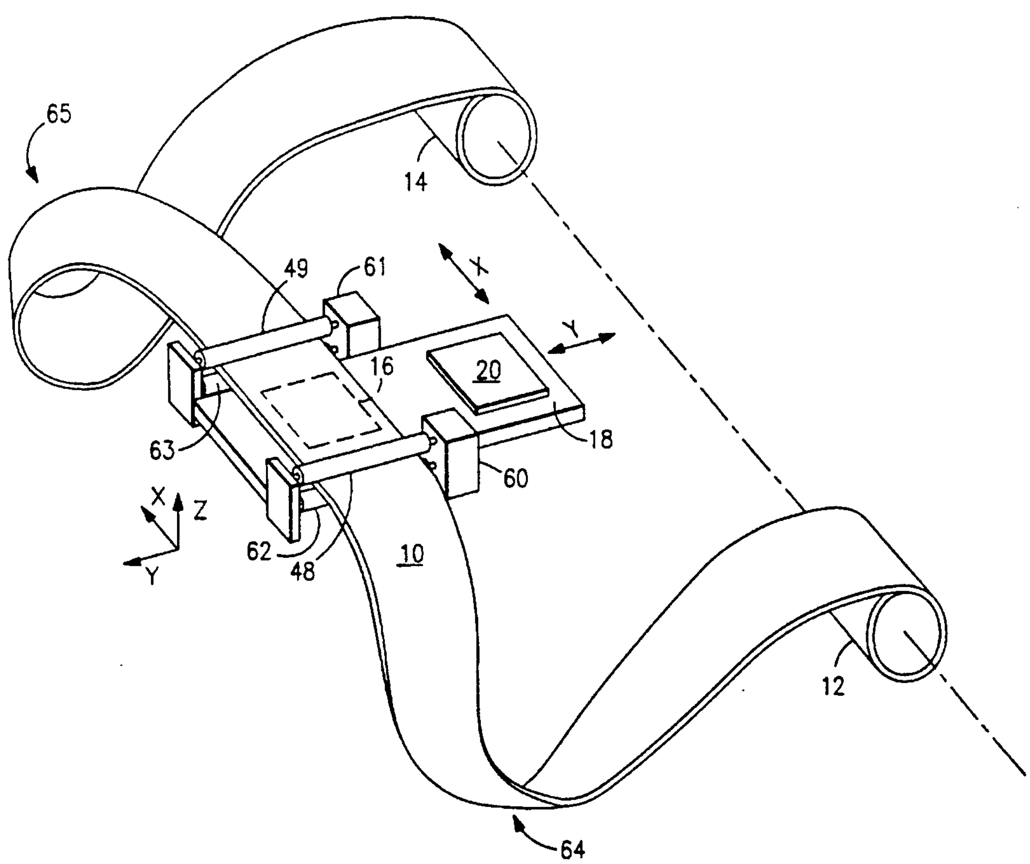
5,198,857	3/1993	Goto	355/53
5,291,240	3/1994	Jain	355/53
5,563,095	10/1996	Frey	437/141

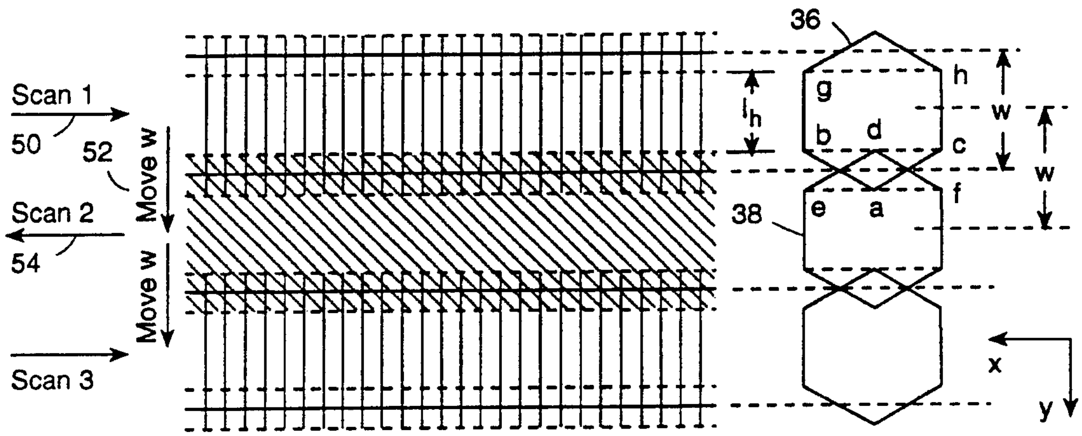
Primary Examiner—Arthur T. Grimley
Assistant Examiner—Herbert V. Kerner
Attorney, Agent, or Firm—Carl C. Kling

[57] **ABSTRACT**

A projection imaging system is described for patterning large, flexible substrates at high exposure speeds and desired resolution, the substrates being in the form of a continuous band fed from a roller for cost-effective electronic module manufacturing. From the continuous band, segments of one panel size are sequentially exposed one at a time. The segment being exposed is held rigidly on a scanning stage, on which is also mounted a mask containing the pattern to be formed on the substrate. The imaging subsystem is stationary and situated above the scanning stage. The mask is illuminated with a hexagonal illumination beam and a region of similar shape is imaged on the substrate. The stage is programmed to scan the mask and substrate simultaneously across the hexagonal regions so as to pattern one whole panel. Provision is made for suitable overlap between the complementary intensity profiles produced by the hexagonal illumination, which ensures seamless joining of the scans and uniform patterning of an entire panel without image stitching errors. For handling the roll substrate so that the substrate segment being exposed remains held rigidly to the scanning stage while the stage moves it in two dimensions without damaging the integrity of the substrate band, mechanisms are provided in the projection system which include provision of managed slack lengths in the substrate band, controlled rotary motions of the supply and take-up substrate rollers, and synchronized, laterally sliding assemblies for the rollers.

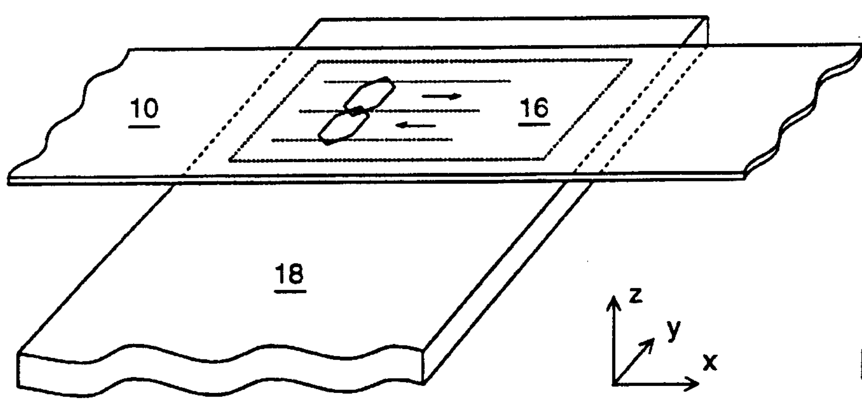
37 Claims, 6 Drawing Sheets





36
Scan 1
50
52
Move w
Scan 2
54
Move w
Scan 3
l_h
g
h
b
d
c
w
w
f
e
a
38
x
y

Fig. 2



10
16
18
z
y
x

Fig. 4

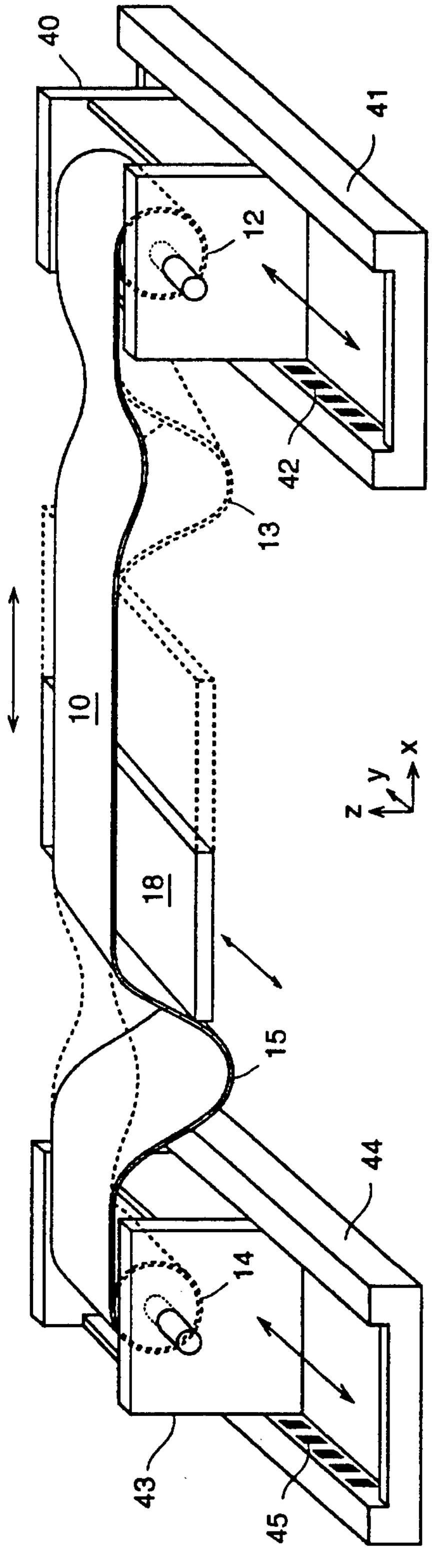

40
41
12
42
13
10
18
15
44
14
43
45
z
y
x

Fig. 8

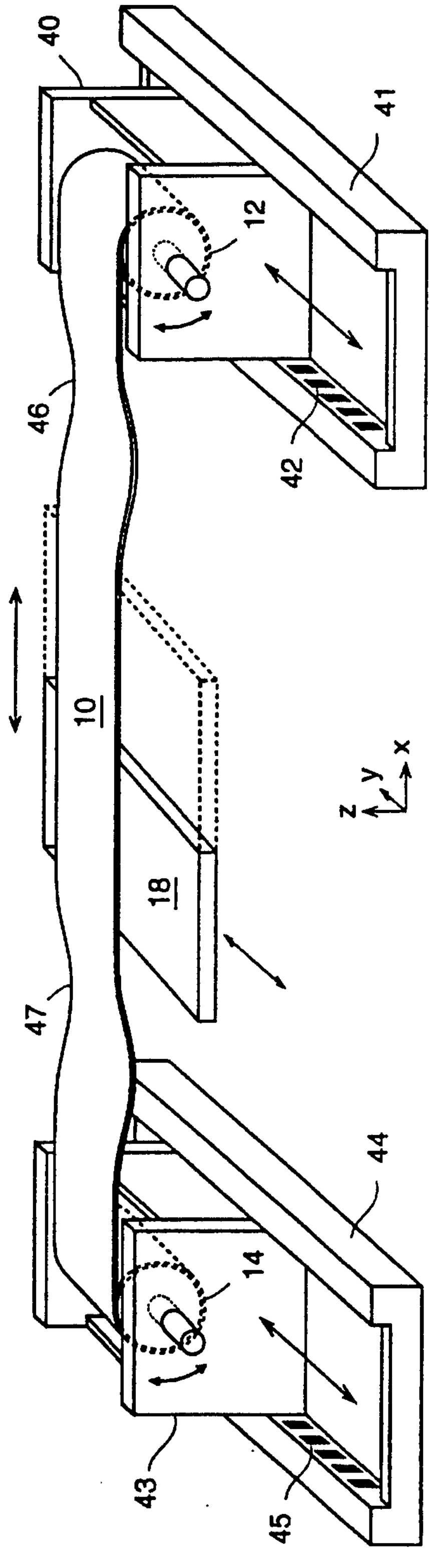

40
41
12
46
42
10
18
47
44
14
43
45
z
y
x

Fig. 9

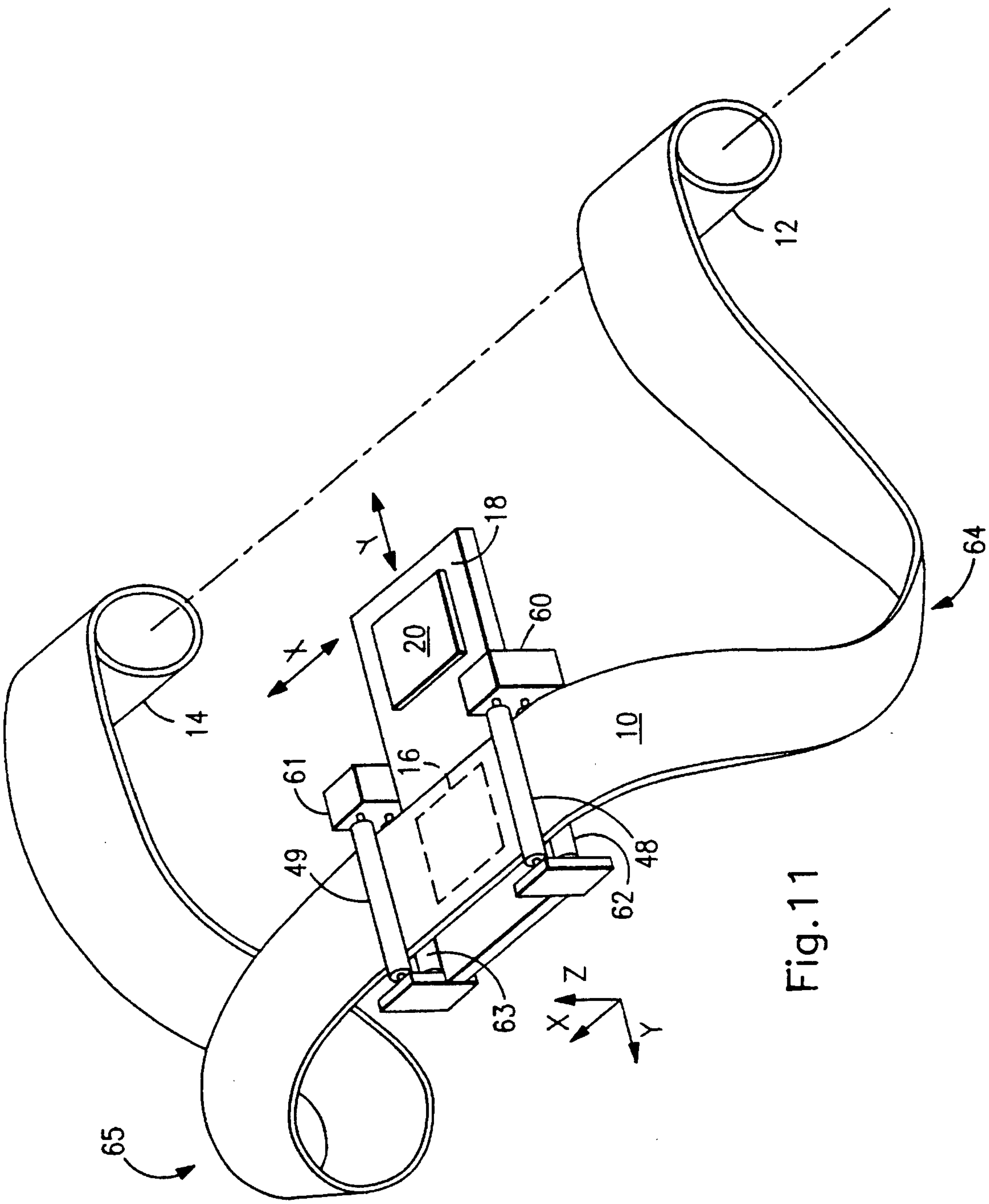


Fig.11

of scanners uses a reflective ring-field imaging system. Exposures are made by scanning the mask and the substrate across an illumination beam in the shape of an arc, which is necessitated by the geometry of the zone of good image correction. The scanning ring-field imaging concept requires primary imaging mirrors that are approximately three times larger than the size of the substrate. As a result, such scanners, although capable of good resolution, are extremely expensive and incapable of handling most large panel sizes. Their throughputs are also low. Another type of existing scanning tool uses a Dyson optical system in which the mask and substrate are mounted on the two arms of an U-box-shaped stage within which the imaging optical assembly hangs as a cantilever. Such system configurations have severe performance limitations, both mechanically and optically. Their imagery is poor due to Abbe errors and flexural bending, and their throughput is low due to inefficient optical field utilization.

A focused-beam direct-writing system uses an ultraviolet or blue laser in a raster scanning fashion to expose all the pixels, one at a time, on the substrate. The laser beam is focused on the resist-coated board to the desired spot size. The focused spot is moved across the board in one dimension with a motor-driven scanning mirror. In conjunction, the stage holding the board is translated in the orthogonal dimension with a high-precision stepping motor. Simultaneously, the laser beam is modulated (typically, acousto-optically) to be either directed to the desired location on the board or deflected away. Thus, by driving the modulator and the two motors with appropriately processed pattern data, the entire board can be directly patterned. Of the many focused-beam direct-write systems currently available, the offered resolution varies from 0.5–1.0 mil for printed circuit board patterning to under a micron for systems designed for mask-making applications for IC lithography. Since transfer of the pattern information by such tools takes place in a slow, bit-by-bit serial mode, typical substrate exposure times can range from 2 minutes to several hours per sq. ft., depending upon the resolution and the complexity of the pattern data. Direct-write systems, therefore, are suitable only for applications such as mask fabrication and prototyping, and highly unattractive for cost-effective volume manufacturing.

Holographic imaging systems utilize a mask which is a hologram of the pattern to be imaged, such that when "played back", it projects the original pattern onto the substrate. The mask is generated by encoding the diffraction pattern from a standard mask in a volume hologram. Generally, for all but the simplest patterns, fabrication of the holographic mask requires numerous processing steps. In a holographic lithography system, the burden of imaging is placed entirely on the mask. Holographic imaging systems suffer from poor diffraction efficiency and are applicable, at best, for imaging of very periodic patterns of not very high resolution. If the pattern is not periodic, the imaging resolution degrades. Holographic masks are also considerably more expensive to generate, which is made further prohibitive when masks for many different layers are required for the substrate.

Related Prior Art

Large-area exposure systems that eliminate all of the above limitations have been described by this inventor in his previous patents, including: U.S. Pat. No. 4,924,257, Scan and repeat high-resolution lithography system, issued May 8, 1990; U.S. Pat. No. 5,285,236, Large-area, high-throughput, high-resolution projection imaging system, issued Feb. 8, 1994; and U.S. Pat. No. 5,291,240, Nonlinearity-compensated large-area patterning system, issued Mar. 1, 1994. In these patents, the inventor has described exposure systems that can pattern large substrates by an efficient seamless scanning technique. The illumination system is designed to produce a hexagonal exposure region. Seamless joining of scans is achieved by partial overlap between adjacent scans, which produces a uniform exposure of the entire panel due to integration of complementary intensity profiles. The systems described in these prior patents are attractive for patterning substrates which are in the form of rigid, discrete panels, but are unable to handle flexible substrates which are in the form of a continuous sheet-roll fed from one roller and taken up by another roller after exposure. As already pointed out above, a system that provides the capability to pattern substrates in a roll-to-roll process will be a significant advantage in the manufacturing of electronic modules. This invention describes such a system.

SUMMARY OF THE INVENTION

This invention describes a projection imaging system that can pattern very large, flexible substrates at very high exposure speeds and any desired image resolution, the substrates being in the form of a band, roll fed from a supply roller, for very cost-effective manufacturing of a variety of electronic modules. From the continuous roll substrate, a segment the size of one panel is exposed at a time in the patterning system; after exposure the segment is made to exit from the patterning system, the next segment is fed and exposed, and so on. The segment being exposed is held rigidly on a scanning stage, on which is also mounted a mask containing the pattern to be formed on the substrate. The mask is imaged onto the substrate by a 1:1 projection system which is stationary and situated above the scanning stage. The mask is illuminated from below with a hexagonal illumination beam which causes a patterned region of similar shape to be imaged on the substrate. The stage is programmed to scan the mask and substrate simultaneously across the hexagonal regions so as to pattern one whole panel. Suitable overlap, between the complementary intensity profiles produced by the hexagonal illumination configuration, ensures seamless joining of the scans.

Additional important elements of this patterning system include the mechanisms for handling the roll substrate. The key requirement in the design of these mechanisms is that, on the one hand, the segment (panel) being exposed must be held rigidly on the stage and be free to move in two dimensions with the scanning stage; and on the other hand, the segment must be part of a continuous roll and the mechanism must be able to feed and extract the roll material into and from the rigid stage one panel-size at a time without impacting the integrity of the sheet. This invention describes several embodiments for accomplishing these requirements.

It is thus the object of this invention to provide a high-throughput, high-resolution, projection patterning system for large, flexible, roll-fed, electronic-module substrates.

It is another object of the invention to provide an exposure system that images large substrates by overlapping seamless scanning using a small-field projection system and a single planar stage assembly.

It is a more specific object of this invention to provide mechanical transport systems that enable both rigid mounting of a flexible substrate during two-dimensional scanning exposure, and supply and take-up of the flexible roll substrate without interfering with the scanning or damaging the mechanical integrity of the substrate.

tion which are applicable to all embodiments to be described in detail in the following. Features which are specific to a particular embodiment will be discussed in the context of the relevant embodiment. **10** represents the flexible substrate which is supplied from supply roller **12** and, after exposure, taken up on take-up roller **14**. The exposure system exposes one segment, **16**, of the size of one panel, at a time. The segment **16** of the flexible substrate is rigidly held on a scanning stage **18** by vacuum; this is further discussed below with reference to FIG. **3**. On the stage **18** is also mounted a mask **20** which contains the pattern to be produced on each substrate panel, such as **16**. The mask pattern is imaged by a projection lens **22** on to the substrate panel **16**. The optical imaging path also contains a fold mirror **24** and a reversing unit **26**. The projection lens **22** is a refractive lens system, and the reversing unit **26** ensures that the orientation of the image on the substrate is the same as that of the pattern on the mask. The mask is illuminated from below by an illumination system **28**, which would typically comprise a light source and additional optical units and components for beam shaping, uniformizing and turning. The output of the illumination system **28** is delivered to the mask **20** after further processing by lenses **30** and **32** and mirror **34**, leading to uniform illumination of a hexagonal region on the mask

The seamless scanning exposure mechanism has been described in detail in this inventor's previous patents cited above, and is summarized here with the illustration of FIG. **2**. The single planar stage **18** (FIG. **1**) causes the mask **20** and the substrate segment (panel) **16** to scan in unison along the x-axis across their respective illuminated regions to traverse the length of one panel. The stage then moves along the y-axis by an effective scan width (shown as w, **52**, in FIG. **2**). Now the substrate and mask are again scanned along x as before, after which they are laterally moved along y, and the process is repeated until the entire panel is exposed. In FIG. **2**, the hexagons **36** and **38** represent the illuminated regions on the substrate for scans **1** (**50**) and scan **2** (**54**). The y-movement after each x-scan is given by $w=1.5\ l_h$, where l_h is the hexagon side-length. In scan **1**, the region swept by the rectangular portion b-g-h-c of hexagon **36** is not overlapped by any portion of scan **2**. However, the region swept by the triangular segment a-b-c of hexagon **36** in scan **1** is re-swept in scan **2** by the triangular segment d-e-f of hexagon **38**. When the doses from these triangular segments are integrated, the cumulative exposure dose anywhere in the overlapping region is the same as in the non-overlapping regions, thus producing a seamless, uniform exposure over the whole panel.

The description above has illustrated how the patterning system concept using hexagonal seamless scanning enables the designer to deliver the desired resolution over very large substrate areas efficiently, provided the substrate being exposed is a discrete, rigid panel. We now show how to construct a patterning system that achieves the above objectives when the substrate is flexible and is fed from a continuous roll. Returning to FIG. **1**, after a segment **16** of the roll **10** is positioned on the stage **18**, it is held firmly by vacuum, as shown in FIG. **3**. Stage **18** is constructed with several vacuum ports, such as **19**, in the region where a substrate segment is to be held. These ports are sufficiently small in size to ensure that the vacuum grip does not cause dimpling of the substrate, and they are large enough in number to keep the entire segment flatly mounted on the stage. Exposure is made by scanning the substrate along the x-axis several times, while stepping it by the effective scan width between successive scans, as described above and further illustrated in FIG. **4**. To permit the scanning and stepping movements, the following mechanisms are implemented in the patterning system.

The simplest mechanism for handling the continuous flexible substrate in the patterning system is shown in FIGS. **5** and **6**. Here, in the flexible substrate roll, certain lengths of slack are introduced in the x-direction on both sides of the scanning stage. These slack lengths are shown as **13** and **15** in FIGS. **5** and **6**. As the stage **18** scans along the positive x-direction, the slack **13** increases and the slack **15** decreases; when the stage scans along the negative x-direction, the slack **13** decreases and the slack **15** increases. Thus, the slack lengths in the substrate material permit uninhibited scanning movement of the stage without interfering with the rollers. Additionally, the slacks **13** and **15** are designed to be of suitable lengths so that they also permit uninhibited stepping movement of the stage in the y-direction without causing wrinkling that may damage the mechanical integrity of the substrate; this is illustrated in FIG. **7**.

A second embodiment of the high-throughput roll-to-roll patterning system is illustrated in FIG. **8**. It comprises a mechanism that enables linear movement of the supply and take-up rollers (**12** and **14**) in a lateral direction (i.e., along the y-axis), such movement being synchronized with the stepping of the scanning stage **18** that takes place between successive x-scans. The supply roller **12** is housed in supply roller assembly **40** which is capable of moving in the slide **41** under the control of a drive mechanism **42** (which, e.g., can be a linear motor). Similarly, the take-up roller **14** is housed in take-up roller assembly **43** which is capable of moving in the slide **44** under the control of a linear motor **45**. Thus, after each scan in the x-direction, as the scanning stage **18** steps in the y-direction by a distance equal to the effective scan width (shown as w in FIG. **2**), both the supply and take-up roller assemblies **40** and **43** move synchronously in the y-direction by the same amount. The scanning motion of the stage **18** in the x-direction is facilitated, as shown previously in FIGS. **5** and **6**, by provision of the slack lengths **13** and **15**. It is clear that an advantage of the embodiment of FIG. **8** is that at no time does one portion of the roll material move laterally with respect to the rest. Thus, no additional slack lengths are required to accommodate the y-axis motion of the stage, and the risk of damaging the substrate material by wrinkling is significantly reduced.

Another embodiment of the invention is shown in FIG. **9**. In this system configuration, the supply and take-up rollers **12** and **14** are provided with the capability of turning around their respective axes in synchronism with the x-direction scanning of the stage **18**. Specifically, as the stage moves in the positive x-direction, the supply roller **12** turns clockwise to take up the slack (**13** in FIG. **8**) that would otherwise be generated; and in synchronism, the take-up roller **14** also turns clockwise to release the extra length of the substrate material that would have otherwise been given by the slack **15** in FIG. **8**. When the stage **18** moves in the negative x-direction, both rollers turn counter-clockwise, the roller **12** releases the necessary additional material, and the roller **14** takes up the released material. The motion of the stage **18** in the y-direction is accommodated, as in the embodiment of FIG. **8**, by the provision of y-movement of the roller assemblies **40** and **43** in their respective slides **41** and **44**. The major advantage of the embodiment of FIG. **9** is that the stage is able to move unimpeded in both x- and y-directions without requiring the substrate roll to have any slack lengths, thus eliminating the possibility of any mechanical damage due to wrinkling. Even so, it is beneficial to provide small

tional step-and-repeat tools, are eliminated. The scanning exposure concept also minimizes the non-exposure overhead time responsible for significant throughput limitation in steppers.

(iv) Due to its 'batch' exposure mode, it eliminates the severe throughput limitations of direct-write systems which expose pattern pixels in a serial fashion.

(v) With its hexagonal illumination configuration, the system of this invention provides maximum field utilization and very high scanning efficiency, enabling it to deliver high throughputs using small-size optics modules, thus keeping system costs low.

(vi) Anvik's modular system design concept permits rapid construction of the exposure system in different user-specified configurations, without requiring an entire new development program for each configuration.

(vii) The modular design concept also provides upgradability. Unlike in prior-art lithography tools, since the major subsystems (illumination, imaging, stage, alignment) in this system are mutually non-interfering, performance can be taken to a higher level by upgrading the appropriate module, without having to retool completely.

(viii) By enabling very short exposure times, the system allows full throughput benefits to be realized from the significantly lower overhead time in roll-to-roll processing. In other patterning tools where the exposure times are significantly greater, the benefit of low overhead time in roll-to-roll processing is lost.

(ix) The system described in this invention is highly versatile. By using an excimer laser as a light source, it provides high-throughput capability for patterning of a variety of photoresists as well as via formation in both photosensitive and photo-ablative dielectrics, thus lowering capitalization costs in a manufacturing plant.

Method of Operation

The invention describes a method of providing a high-throughput, high-resolution patterning system for large, roll-fed substrates using the following steps:

1. Providing a stage for holding both a panel-size segment of the substrate roll and a mask, and capable of scanning longitudinally in one direction, and also capable of moving laterally in a direction perpendicular to the scan direction;

2. Providing an illumination system which produces radiation of the wavelength and intensity required by the photosensitive substrate material, and which produces on the mask an illumination region in the shape of a regular hexagon of side l_h which can be inscribed within the image field of the projection assembly described in step 3 below;

3. Providing a projection imaging assembly of magnification 1:1, which has an image field size which is substantially smaller than the size of a panel-segment of the substrate, and which is designed to produce a 1:1 image of the illuminated region of the mask on the substrate with the required resolution;

4. Providing an optical reversing unit which, in conjunction with the projection assembly of step 3, helps produce an image on the substrate that is in the same orientation as the object pattern on the mask;

5. Providing rollers to supply and take up flexible substrate material in the form of a band of a sheet, and providing mechanisms to affix a panel-segment of the substrate on the stage so as enable the stage to move both longitudinally and laterally without damaging any portion of the roll-to-roll substrate;

6. Scanning the stage so that the length of the mask traverses across the hexagonal illumination region described in step 2;

7. Stopping the stage momentarily after completion of a scan across the length of the mask, moving the stage by a distance equal to 1.5 l_h in a direction perpendicular to the scan direction, and resuming the scanning of the stage in a direction opposite to the scan direction in step 5;

8. Repeating steps 6 and 7 until exposure of one entire panel-segment of the substrate is completed;

9. Releasing the exposed panel-segment of the substrate from the stage, releasing an equal length of substrate from the supply roller, affixing another panel-segment of the substrate on the stage, winding up an equal length of substrate on the take-up roller, and repeating steps 6–8 above until exposure of the entire new panel-segment of the substrate is completed; and

10. Repeating steps 6–9 above until exposure of the whole roll of substrate material is completed.

For additional precision in patterning, the method of operation may further include the step of periodically realigning the mask and substrate with respect to each other during the steps 6–10 above.

System Design Example

In this section, we present an example of a system design based on this invention. We describe the design parameters, both optical and mechanical, for the system, and also discuss the hardware subsystems suitable for incorporating in the tool. The projection assembly is a refractive lens with a magnification of 1:1. It has a numerical aperture (NA) of 0.0216 (f/23.2) which provides a resolution of 10 µm, more than adequate to meet the linewidth requirement of 15 µm for the next several years for electronic modules made on flexible substrates. In fact, it is always desirable to have an optical design resolution better than the minimum feature size to be patterned; this gives both a comfortable manufacturing process window and good line-edge definition. The imaging system has a depth of focus of 660 µm. This will comfortably accommodate the flatness tolerance of 125 µm typical of most flexible substrates. The projection lens has an image field of 50 mm diameter and is made of all fused silica elements. The light source is a xenon chloride excimer laser operating at a wavelength of 308 nm with an average power output of $\geqq$150 W. The choice of an excimer laser as the light source as contrasted with a mercury are lamp is based on the fact that the optical efficiency for the useful UV power delivered to substrate is significantly greater for the laser (50–60%) than for the lamp (<2%).

The x-y scanning stage system is designed to handle substrate widths of up to 14 inches. This single planar stage holds the mask and the substrate side-by-side; the mask is held mechanically and the to-be-exposed segment of the substrate by vacuum. The stage is of the crossed roller bearing type with linear motor drives, with position and velocity control being provided by linear encoders. Other optical modules in the exposure tool include a condenser subsystem, which comprises an input lens assembly for beam shaping and focusing, an intensity homogenizer, a relay lens assembly, and some steering mirrors. Additional components in the imaging optical train include a reversing unit and a folding mirror. The homogenizer employs a multiple-reflection light tunnel configuration. The reversing unit is be a split-roof mirror system. All mirrors in the system are high-reflectivity, multilayer dielectric-coated mirrors. All lens-element surfaces have anti-reflection

where l_h is the length of each side of said regular-hexagon-shaped illuminated region on the substrate.

4. A projection imaging system according to claim 1, further characterized in that

said illumination subsystem (18) provides radiation from a mercury lamp.

5. A projection imaging system according to claim 1, further characterized in that

said illumination subsystem (18) provides pulsed radiation from an excimer laser.

6. A projection imaging system according to claim 1, further characterized in that

said stage subsystem (18) comprises a planar stage with a first position for said mask (20) and a second position for said substrate band segment (16), the two positions being aligned in the same plane for imaging by said projection subsystem (22–26).

7. A projection imaging system according to claim 1, further characterized in that

said stage subsystem (18) comprises a dual-platform stage with a first position on a first platform for said mask (20) and a second position on a second platform for said substrate band segment (16), the two positions being aligned in parallel planes for imaging by said projection subsystem (22–26).

8. A projection imaging system according to claim 1, further characterized in that

said stage subsystem substrate segment locking means comprises vacuum means (19) for holding a substrate segment (16) locked in place during exposure by multiple scans.

9. A projection imaging system according to claim 1, further characterized in that

said stage subsystem substrate segment locking means comprises a set of stage subsystem entry and stage subsystem exit platens (48,49) for holding a segment (16) of said substrate band (10) locked in place during exposure by multiple scans.

10. A projection imaging system according to claim 9, further characterized in that

said stage subsystem (18) entry and exit platens (48,49) have respective motors (60,61) to advance said substrate band (10), and the bottom surface of said substrate band (10) is against the surface of said stage subsystem (18).

11. A projection imaging system according to claim 1, further characterized in that

said stage subsystem substrate segment locking means comprises both a vacuum means (19) and a set of stage subsystem entry and stage subsystem exit platens (48, 49) for holding a segment (16) of said substrate band (10) locked in place during exposure by multiple scans.

12. A projection imaging system according to claim 1, further characterized in that

said stage subsystem substrate locking means comprises a stage subsystem entry set and a stage subsystem exit set of pinch platens (48–49, 62–63) for holding a segment (16) of said substrate band (10) locked in place during exposure by multiple scans.

13. A projection imaging system according to claim 12, further characterized in that

said stage subsystem (18) entry and exit pinch platen sets (48,62/49,63) have respective entry and exit platen motors (60,61) to advance said substrate band (10).

14. A projection imaging system according to claim 1, further characterized in that

said stage subsystem substrate locking means comprises both a vacuum means (19) and a stage subsystem entry set and a stage subsystem exit set of pinch platens (48,49; 62,63) for holding a segment (16) of said substrate band (10) locked in place during exposure by multiple scans.

15. A projection imaging system according to claim 1, further characterized in that

said substrate presenting means and said control means provide stress relievers operating on said substrate band (10) on entry and exit sides of said stage subsystem (18) so that a substrate band (10) segment (16) remains locked in place on said stage subsystem (18) while being scanned along the longitudinal direction of the substrate band (10), whereby said substrate band (10) remains undamaged.

16. A projection imaging system according to claim 15, further characterized in that

said substrate presenting means comprises supply roller means (12) and take-up roller means (14) and said stress relievers are slack lengths (13,15/64,65) sufficient to permit scanning along the longitudinal direction of the substrate band (10) without disturbing the lock of substrate band (10) segment (16) to said stage subsystem (18) and without damage to said substrate band (10).

17. A projection imaging system according to claim 16, further characterized in that

said stress relieving slack lengths (13,15/64,65) are sufficient to permit scanning along the longitudinal direction of the substrate band (10) and stepping along the lateral direction without disturbing the lock of the substrate band segment (16) to said stage subsystem (18) and without damage to said substrate band (10).

18. A projection imaging system according to claim 17, further characterized in that

(a) said supply roller (12) and said take-up roller (14) have their axes along the same direction;

(b) said substrate band (10) makes two 90 degree turns in its path from said supply roller (12) to said stage subsystem (18) to said take-up roller (14);

(c) said control means controls delivery of said substrate band (10) to provide slack lengths in said two 90 degree turns, to accommodate both longitudinal motion and lateral motion of said stage subsystem (18); and

(d) said control means causes said rollers to rotate to release new substrate length from said supply roller (12) and take up exposed substrate length on said take-up roller (14).

19. A projection imaging system according to claim 18, further characterized in that

said control means causes said supply roller (12) and said take-up roller (14) to rotate oppositely.

20. A projection imaging system according to claim 18, wherein said stress-relieving slack length between said supply roller (12) and said stage subsystem (18) causes inversion of the plane of said substrate band (10) and said stress-relieving slack length between said stage subsystem (18) and said take-up roller (14) causes re-inversion of the plane of said substrate band (10).

21. A projection imaging system according to claim 18, further characterized in that

said substrate band (10) is wound from above on one of said supply roller (12) and said take-up roller (14) and from below on the other, and said control means causes said supply roller and said take-up roller to rotate in the same direction.

(c) substrate take-up means (**14/43**) for accepting such semi-flexible substrate band (**10**) from said imaging means; and

(d) supply stress-relieving means intermediate said substrate supply means and said imaging means; and

(e) take-up stress-relieving means intermediate said imaging means and said substrate take-up means.

33. A high-throughput. projection patterning system according to claim **32**. wherein said supply stress-relieving means is a slack length of said substrate band (**10**) that causes inversion of the plane of the substrate band (**10**) and said take-up stress relieving means is a slack length that causes re-inversion of the plane of the substrate band (**10**).

34. A high-throughput. projection patterning system according to claim **32**. wherein said supply and take-up stress relieving means are controlled-motion mechanisms for moving the respectively related substrate supply means and substrate take-up means synchronously with movement of said stage subsystem (**18**).

35. A high-throughput. projection patterning system according to claim **32**. wherein said supply and take-up stress relieving means comprise substrate slack length control mechanisms for keeping the related substrate supply means and substrate take-up means isolated from longitudinal and lateral movements of said imaging means.

36. A high-throughput. projection patterning system according to claim **35** wherein said supply stress relieving means and take-up stress relieving means include means for managing the isolation of the related substrate supply means and substrate take-up means from longitudinal and lateral movements of said imaging means.

37. A high-throughput. projection patterning system comprising

(a) means for feeding a substrate band (**10**) to present a substrate band segment (**16**) for imaging at a imaging station;

(b) locking means to affix said substrate band segment (**16**) and a mask (**20**) to said imaging station in a fixed mutual spatial relationship;

(c) an illumination subsystem for illuminating a polygonal region on said mask;

(d) a projection subsystem for imaging said illuminated polygonal mask region onto said substrate band segment;

(e) means for providing a sequence of scanning motions of said illumination subsystem and said projection subsystem. relative to said fixed mask (**20**) and said fixed substrate band segment (**16**);

whereby said substrate band segment (**16**) is exposed seamlessly and uniformly by a sequence of overlapping polygonal scans.

* * * * *